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Review **JoPC**

The Impact of Nanotechnology in Transforming Neuro-oncology - A Comprehensive Review

Akbar J[1], Gunapati Rama Mohan Reddy[2], Venkata Prasanna DP[3], Jagatheesan Alagesan[4], Rajameena R[5], Prathapavarma Digala[6], Shaik Ibrahim Khalivulla[7,]*

Abstract

The treatment of central nervous system (CNS) tumours, including aggressive malignancies like glioblastoma, faces significant challenges. The blood–brain barrier (BBB) blocks nearly 98% of small-molecule drugs from achieving therapeutic levels in the brain, and the heterogeneity of these tumours frequently contributes to treatment resistance and poor outcomes. Traditional approaches, including chemotherapy and radiotherapy, are hindered by systemic toxicity and inadequate drug penetration. Nanotechnology provides a promising alternative, as nanoparticles (NPs) can be designed to cross the BBB and selectively transport therapeutic agents to the tumour site. Their unique properties, including small size, enhanced stability, and customizable surface chemistry, allow for improved drug solubility, sustained release, and targeted delivery, which reduces harm to healthy brain tissue. This approach is not limited to drug delivery; nanotechnology also enhances diagnostic capabilities through advanced imaging contrast agents and theranostic platforms that combine diagnosis and therapy. By integrating with existing treatments, nanotechnology can act as a radiosensitizer to boost the effectiveness of radiation and as a delivery system for gene therapy and immunomodulatory agents. Personalized nanomedicine is also emerging, leveraging a patient's genetic and molecular profile to create tailored treatments that address the heterogeneity of brain tumours. Despite its immense promise, the field faces hurdles, including the potential for long-term neurotoxicity, challenges in large-scale manufacturing, and the need for a clear regulatory framework. Future directions involve leveraging artificial intelligence to optimize NP design, developing biodegradable nanomaterials, and creating highly advanced systems like stimuli-responsive nanorobots to further improve efficacy and safety in neuro-oncology.

Keywords: Nanotechnology, neuro-oncology, drug delivery, blood-brain barrier (BBB), glioblastoma, personalized medicine

***Author for Correspondence**
Shaik Ibrahim Khalivulla

[1]Assistant Professor, Faculty of Physiotherapy, Dr. M.G.R. Educational and Research Institute, Maduravoyal, Chennai, Tamil Nadu, India
[2]Assistant Professor, Department of Pharmacology, Government Medical College, Paderu, Alluri Seetharama Raju District, Andhra Pradesh, India
[3]Assistant Professor, Department of Ophthalmology, Sri Balaji Medical College, Hospital & Research Institute, Renigunta, Andhra Pradesh, India
[4] Professor and Dean, Department of Physiotherapy, School of Paramedical Allied and Health Care Sciences, Mohan Babu University, Tirupati, Andhra Pradesh, India
[5]Senior Assistant Professor, Department of Neurological and Psychosomatic Disorders, Acharya's NR Institute of Physiotherapy, Acharya Institutes, Soladevanahalli, Bangalore, Karnataka, India
[6]Associate Professor, Department of Medical Laboratory Technology, School of Medical and Allied Sciences, MNR University, Fasalwadi, Sangareddy, Telangana, India
[7]Assistant Professor, Department of Biological and Chemical Sciences, School of Liberal Arts and Sciences, Mohan Babu University, Tirupati, Andhra Pradesh, India

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INTRODUCTION

Neuro-oncology is a vital subspecialty that relies on a multidisciplinary team to manage central nervous system (CNS) disorders, including primary and metastatic brain tumours. The treatment leads to neurotoxicity, and quality of life issues [1]. CNS tumours can be benign or malignant, with types like gliomas, astrocytomas, and meningiomas. Glioblastoma is the most common and aggressive malignant brain tumour, while meningioma is the most prevalent benign type [1,2]. In the U.S. and Canada, CNS tumours are the most frequent cancers in young individuals and the second leading cause of cancer-related deaths in those under 19. A 2019 study reported a glioma incidence rate of 5.5 per 100,000 individuals, and an Iranian study found 6 out of every 100,000 people were diagnosed with CNS tumours [3, 4]. These tumours significantly impact patients and their families, causing varied symptoms due to pressure on brain or spinal cord tissue, necessitating early and accurate diagnosis to prevent long-term disabilities. A major hurdle in treating CNS tumours is the blood-brain barrier (BBB), a highly selective interface covering approximately 12 to 18 square meters in the adult human brain. This barrier, which controls substance passage into the CNS, prevents about 98% of small-molecule drugs and almost all large-molecule therapeutics from reaching sufficient concentrations in the brain. Even small molecules like histamine (~100 Daltons) do not readily cross it. While brain tumours alter the BBB into a blood-tumour barrier (BTB) with varied permeability, effective drug delivery remains challenging due to the BTB's inconsistent nature and the tumour's vascular architecture. Researchers are actively developing new strategies to bypass or modulate these barriers to improve treatment outcomes for CNS tumour patients [5, 6].

ROLE OF NANOTECHNOLOGY IN MEDICINE

Nanomedicine, utilizing nanomaterials and nano-electronic biosensors, is transforming healthcare. It offers significant advancements in early disease detection, precise diagnosis, targeted therapy, and follow-up treatment. For instance, gold nanoparticles labeled with DNA are revolutionizing genetic sequencing by identifying specific genetic markers. Nanomedicine also plays a crucial role in tissue engineering, facilitating the regeneration of damaged tissues and potentially revolutionizing organ transplants. It further enables treatments at the molecular level, deepening our understanding of disease mechanisms and leading to more effective therapeutic strategies. Nanotechnology is widely used in molecular biology for targeted drug delivery, diagnostics, biosensing, tissue engineering, and cell culture. Various nanotechnology-based platforms, including fullerenes, carbon nanotubes, quantum dots, and liposomes, are under development [7, 8]. These systems are particularly beneficial for treating conditions like cancer, diabetes, and viral/fungal infections, and are being explored for gene therapy. By delivering drugs directly to target sites, nanotechnology enhances therapeutic effectiveness, minimizes side effects, and improves safety. In diagnostics, it contributes through contrast agents, fluorescent markers, and magnetic nanoparticles, enabling high-precision imaging and disease detection. Furthermore, nanotechnology allows for the modification of drug properties like solubility and stability, supporting controlled and site-specific drug release for more efficient and personalized treatments. Nanotechnology is a key player in overcoming the limitations of traditional drug delivery, such as poor drug stability, low absorption, and off-target distribution. By creating nanoscale materials (polymers, lipids, metallic compounds), nanotechnology enables the precise delivery of drugs to specific areas of the body [9]. Nanoparticles (NPs) enhance drug properties by improving bioavailability, biodistribution, and cellular uptake while reducing toxicity. These tiny systems prevent premature drug release and facilitate controlled delivery to target sites, significantly boosting therapeutic efficacy and minimizing side effects. NPs are especially valuable in drug development, where they address the challenges of correlating a drug's in vitro activity with its in vivo absorption, metabolism, toxicity, and excretion [10].

NPs are often administered intravenously, though intraventricular injection can be used for improved drug distribution and to bypass the blood-brain barrier (BBB), despite its invasiveness and rapid cerebrospinal fluid turnover. The BBB tightly regulates molecular flow into the brain, posing a significant challenge for treating central nervous system (CNS) conditions, especially malignant brain tumours like glioblastoma, which have a poor prognosis due to BBB impermeability [10]. NPs offer a novel approach to overcome the BBB due to their unique physical and chemical properties. Their small size (ideally 1-1000 nm, with permeability significantly decreasing above 200 nm), low toxicity, and controlled drug release make them highly effective. NPs can also be surface-modified with proteins to target specific receptors. Enhanced transport of NPs across the BBB can occur through both active and passive mechanisms, including transcytosis, carrier-mediated transport, and passive diffusion, particularly in areas where the BBB is compromised by tumours. Electrostatic interactions also play a significant role. The BBB's endothelial cells have a negative surface charge, making positively charged NPs well-suited for adsorptive-mediated transcytosis. While highly permeable, positively charged NPs can generate reactive oxygen species, potentially damaging cells [11]. Conversely, cationic nanoparticles can effectively deliver negatively charged genetic material, such as small-interfering RNA, for targeted gene therapy in tumours, as BBB endothelial cells are insensitive to anionic charges [12].

Certain healthy brain regions, such as the choroid plexus and circumventricular organs, naturally lack a BBB, allowing chemicals to diffuse into the brain. Importantly, brain tumours and other medical conditions can disrupt the BBB, creating a brain tumour barrier that is more permeable [13]. This disruption is characterized by decreased tight junction expression (often induced by VEGF secretion from tumour cells), irregular pericyte coverage, altered astrocyte end feet, and basal membrane disruption. In gliomas, BBB disruption is disease-stage dependent and concentrated in the tumour core, with hypoxic regions showing increased VEGF expression and angiogenesis, leading to more permeable blood vessels [14]. This BBB disruption in gliomas is observable by gadolinium accumulation on MRI and correlates with more malignant tumour grades. The diverse forms of NPs including polymeric, liposome, dendrimer, metallic, quantum dots, and nanogels possess varied physical and chemical properties that further enhance their utility in increasing accessibility to brain tumours [15].

Nanotherapy

Currently available cancer treatments include immunotherapy, chemotherapy, radiation and surgery but, due to ineffective drug delivery to the intended place, current medicines do not always work to treat diseases. Acquired medication resistance and pharmacologic or toxicological problems can also lead to failure. Here, one of the primary issues with conventional chemotherapy treatments is the solubility of drugs, which is often low in aqueous solutions. For this reason, in order to be administered parenterally, they must be dissolved in hazardous solubilizing agents [6,8,15,16]. Thus, to prevent systemic toxicity, the dose must be reduced. Due to the benefits of nanoparticles and nanomedicines such as their enhanced water dissolved condition, reduced size, enhanced stability and shelf life, enhanced bioavailability and rates of release, and targeted delivery of biological therapies nanotechnology has the potential to enhance drug delivery and therapy greatly. Nanocarriers or nanoparticles are nanomaterials employed for delivering anticancer agents which have the potential to increase current therapeutic windows and clinical efficacy in managing disease due to their better pharmacogenetic characteristics, increased blood half-life, cellular uptake and distribution volume [17].

Antiretroviral Therapy

Despite significant progress in AIDS control, the disease remains a major global health threat, largely due to the limitations of current therapies like Highly Active Antiretroviral Therapy (HAART). Although HAART has reduced mortality, it fails to completely eliminate the virus from the body's resting $CD4^+$ T cells, a key viral reservoir [18]. Furthermore, many antiretroviral drugs have pharmacological drawbacks, including low stability, poor absorption, adverse side effects, and limited penetration into critical organs like the central nervous system and lymphatic system. For example, drugs like didanosine have low bioavailability, zidovudine can be toxic, and tenofovir can cause renal failure. Additionally, low solubility and limited biodistribution affect drugs like efavirenz and etravirine [19]. These issues, along with challenges in patient compliance and drug interactions, highlight the need for a more effective approach.

Nanotechnology offers a promising solution to these challenges by enabling targeted and sustained drug delivery. Nanoparticles can improve the bioavailability of antiretroviral drugs while minimizing side effects. For instance, nanoparticles made from poly(isohexyl cyanate) and polyhexylcyanoacrylate have been shown to increase drug levels in lymphoid tissues and improve bioavailability [20]. The use of poly(lactic-co-glycolic)acid (PLGA) nanoparticles has demonstrated the ability to sustain drug release in peripheral blood cells for up to 28 days, which could significantly improve patient compliance by reducing dosing frequency [21]. Other nanocarriers, such as dendrimers and solid lipid nanoparticles (SLNs), have been successfully used to deliver drugs to specific cells like macrophages and to improve drug permeability across the blood-brain barrier (BBB), which is crucial for treating HIV-related neurological complications [22].

Various nanoparticle formulations have shown impressive results in overcoming specific drug delivery hurdles. Polybutylcyanoacrylate (PBCA) nanoparticles, for example, have enhanced the permeability of zidovudine and lamivudine across the BBB by as much as 20-fold [23]. Similarly, SLNs have increased the permeability of drugs like stavudine and delavirdine by 4 to 11 times. Liposomal preparations, when designed with specific targeting molecules, have shown enhanced uptake by mononuclear phagocytic cells and greater accumulation in organs of the reticuloendothelial system. The use of transferrin-anchored nanoparticles has also demonstrated improved drug delivery to the brain, further proving the potential for precisely engineered nanocarriers to bypass biological barriers. In summary, nanoparticle-based drug delivery systems offer a viable path to creating safer, more effective, and more patient-friendly HIV/AIDS treatments by improving bioavailability, target specificity, and sustained drug release [24].

Gene and RNA Delivery

Nanoparticles, particularly gold nanoparticles known as nanoflares, function as intracellular nucleic acid sensors. These probes are modified through nucleotide hybridization to complementary, fluorophore-labeled strands, enabling them to detect messenger RNA (mRNA) within cells [25]. Nanoflares have overcome challenges in probe design, demonstrating high sensitivity to fluctuations in RNA transcripts and an excellent signal-to-noise ratio [26]. Their rich polynucleotide coats allow them to penetrate cells without toxic transfection reagents and to measure multiple mRNA transcripts simultaneously. This method is comparable to standard qRT-PCR and can be used to quantify intracellular mRNA at the single live cell level. Therapeutic RNAs, including mRNA, small interfering RNA, and microRNA, are effective anticancer agents because they can either enhance the expression of tumour suppressor genes or silence oncogenes. This RNA-based therapy is considered superior to protein-based therapy due to its relative ease of design and lower production cost. MicroRNAs (miRNAs), the smallest of the non-coding RNAs, are associated with the initiation and progression of various cancers. A single miRNA can repress multiple target genes, and knocking out an oncogenic miRNA can rescue tumour suppressors, offering potential therapeutic benefits. Glioblastoma, a particularly lethal brain tumour, is an example where a specific miRNA, miR-21, is frequently dysregulated. MiR-21 contributes to glioblastoma oncogenesis by inhibiting significant tumour suppressors, making it a clear and promising drug target [27, 28].

Diagnostic imaging enhancement

Identifying and treating brain malignancies in their early stages is challenging, partly because tumours are difficult to define and measure due to the build-up of extracellular fluid. Current neuroimaging techniques like, MRI and CT scans offer detailed anatomical information with resolutions between 25 and 100 µm, they often require contrast agents for better visualization. Other methods, like PET and SPECT, use costly, injectable radioactive tracers for high-sensitivity detection, but their resolution is much lower, typically ranging from 2 to 10 mm. The field of nanotechnology is emerging as a potential solution to these challenges, particularly in preclinical studies. Functionalized nanoparticles made from materials like iron oxide, gold, or quantum dots have shown promise in improving the clarity of brain tumours and other neurological issues in rodent models. These biocompatible nanoparticles can serve as superior contrast agents due to their stability, solubility, and excellent surface chemistry. By combining traditional imaging with nanotechnology, a new field called nanodiagnostics is developing more precise tools for brain tumour diagnosis. Innovations like nanoarrays/ nanochips integrate optical, magnetic, and electrical properties to provide highly accurate data with greater ease. Despite recent advances in detection, the lack of a significant decline in brain cancer death rates highlights the need for further improvements. This includes developing enhanced methods for early detection and creating treatment plans that are more accurately absorbed by cancer cells, minimizing damage to surrounding healthy tissue [28, 29].

Neurosurgery

For a cancer patient to be cured through surgery, the entire tumour, along with any affected lymph nodes and nearby nodules, must be completely removed. This full resection is the single most important factor for long-term survival, and it can improve a patient's survival rates by three to five times. Despite significant advancements in surgical techniques over the last fifty years, the methods for assessing a complete removal haven't changed much. Surgeons still rely on their senses and experience, which can lead to a high false-negative rate, where a surgeon mistakenly believes all tumour tissue has been removed. However, recent technological developments are improving surgical precision. Intraoperative fluorescence-guided surgery uses special dyes and advanced imaging to help surgeons visualize and remove malignant tissue in real time [30]. Dyes like indocyanine green (ICG) and 5-aminolevulinic acid (5-ALA) highlight tumour boundaries, while new imaging devices provide high-definition images to guide the surgeon more accurately. The integration of these imaging techniques with nanotechnology and robotic visualization aims to enhance the safety and extent of tumour removal, ultimately improving patient outcomes [31]. Beyond cancer, nanomaterials are also being developed for other surgical specialties, such as using them to promote bone growth in spine surgeries and to create scaffolds for treating spinal cord injuries.

In addition to surgery, radiation therapy (RT) is a vital cancer treatment that uses ionizing radiation to kill cancer cells. It can be delivered in two primary ways: external beam radiotherapy (EBRT), which directs radiation beams from outside the body, and internal radioisotope therapy (RIT), which uses radioactive materials delivered directly to the tumour. Both are often combined with chemotherapy, a treatment known as chemoradiotherapy, to enhance efficacy [32]. A significant challenge with these treatments is balancing their effectiveness with potential toxicity to healthy tissue. Nanoparticles (NPs) are emerging as a potential solution, as they can act as both drug delivery systems and radiosensitizers [33]. Because tumours have highly permeable blood vessels, nanoparticles can accumulate there more effectively through the enhanced permeability and retention (EPR) effect. This allows them to enhance the effect of radiation on cancer cells while sparing healthy tissue. Nanomaterials like metallic nanoparticles, supermagnetic iron oxides, and quantum dots are being researched for their ability to improve the precision and effectiveness of radiation therapy [34].

Personal Nanomedicine

Personalized nanomedicine is an exciting field that tailors nanotechnology-based therapies to an individual patient's tumour. By incorporating patient-specific molecular and genetic information, this approach aims to increase the effectiveness of targeted therapy while reducing negative side effects. Brain tumours, particularly glioblastoma, are incredibly complex and diverse [35]. This tumour heterogeneity, where cells within the same tumour vary greatly at the genetic and molecular level, is a major reason conventional treatments often fail. Personalized nanomedicine addresses this by designing nanocarriers to match the unique biological features of a patient's tumour. Advances in personalized nanomedicine involve several key strategies. In Targeted Drug Delivery, nanoparticles are engineered to carry chemotherapy drugs and deliver them specifically to tumour cells. By adding molecular markers (ligands) to the nanoparticles, they can selectively accumulate in cancer cells, minimizing damage to healthy brain tissue. In Genomic and Proteomic Integration by analyzing a patient's genetic and protein profiles, researchers can identify specific tumour biomarkers. This information is used to load nanocarriers with drugs that directly target those mutations. Emerging technologies like CRISPR-based gene editing are also being explored for individualized therapy. By

Overcoming the Blood-Brain Barrier (BBB), the BBB is a significant obstacle for delivering drugs to the brain [36]. Personalized nanomedicine uses innovative techniques, such as receptor-mediated transcytosis and ultrasound, to help nanoparticles cross this barrier and reach the tumour. In Nano-Enabled Immunotherapy, nanoparticles are being designed to enhance the body's immune response against tumours [37]. This includes creating nanovaccines with patient-specific tumour antigens to train the immune system to identify and destroy cancer cells. Nanoparticles can also be used to deliver immunomodulatory drugs and modify the tumour's immunosuppressive environment [38].

Despite its promise, personalized nanomedicine faces several challenges. The tumour Complexity, the sheer complexity of tumour heterogeneity makes comprehensive profiling time-consuming and expensive. Researchers are working on new technologies like single-cell sequencing to manage this. Cost and Scalability, the synthesis and customization of nanoparticles for each patient is currently a major economic and logistical hurdle. Regulatory and Ethical Concerns, clear regulatory policies are needed to ensure the safety and efficacy of these highly personalized treatments. Ethical considerations related to patient genetic profiling must also be addressed. Personalized nanomedicine is not meant to be a standalone treatment [39]. Researchers are exploring how it can be combined with existing therapies like radiation, chemotherapy, and immunotherapy. Fusing these strategies could lead to more effective treatments with fewer adverse effects. For instance, nanoparticles can be used to improve the delivery and effectiveness of immunotherapies by carrying checkpoint inhibitors or by altering the immunosuppressive microenvironment that protects tumours from the immune system.

Integration of Nanotechnology with Targeted Therapies

Nanotechnology holds significant promise for overcoming the limitations of conventional therapies in neuro-oncology, particularly by enabling the precise delivery of therapeutic molecules directly to tumour sites while sparing healthy tissue. Despite promising recent developments, more research and technological advances are necessary to address current challenges and fully unlock its potential. One of the key advantages of nanotechnology is its ability to improve targeted drug delivery. Many targeted drugs are ineffective against brain tumours because they struggle to penetrate the blood-brain barrier (BBB) and distribute effectively within the tumour. Nanotechnology addresses this by encapsulating these drugs within nanoparticles. These nanoparticles can be engineered with functionalized ligands, such as those that bind to the epidermal growth factor receptor (EGFR), allowing them to specifically target tumour cells and bypass these distribution issues [40].

Furthermore, nanotechnology provides a powerful solution for overcoming drug resistance, a major hurdle in glioblastoma treatment. Nanoparticles can be designed to co-deliver multiple therapeutic agents in a single carrier, allowing for combination therapy that targets multiple resistance mechanisms at once. They can also be engineered to be "smart," releasing their drug payload only in response to specific tumour-related stimuli, such as changes in pH or the presence of certain enzymes, ensuring the drug is delivered precisely where it's needed. Several strategies have also been developed to enable nanoparticles to cross the formidable blood-brain barrier. Nanoparticles can be surface-functionalized with ligands that bind to receptors on the BBB, facilitating their entry through a process called receptor-mediated transcytosis. Other innovative methods, such as using ultrasound to temporarily disrupt the BBB or employing magnetic guidance to direct nanoparticles to the target site, are also being explored to enhance the effectiveness of these therapies.

Combining Nanotechnology with Radiation Therapy

Radiation therapy is a fundamental treatment for brain tumours, but its effectiveness is often hampered by the potential for damage to healthy brain tissue. To address this limitation, researchers are exploring the use of nanoparticles as radiosensitizers [41]. These tiny particles can boost the tumour-killing capacity of radiation without increasing harm to surrounding normal tissue. For example, gold nanoparticles have shown particular promise by enhancing the absorption of radiation specifically within malignant cells, which could lead to more effective treatment outcomes. Another innovative application of nanotechnology is the use of nanoparticles to deliver radiopharmaceuticals directly to brain tumours [42]. By encapsulating radioactive isotopes within nanoparticles, scientists can achieve highly targeted radiation therapy. This approach minimizes systemic exposure to the patient, reducing unwanted side effects. Preliminary studies in glioblastoma models have shown great promise for this technique, suggesting it could be a way to precisely target cancerous cells while sparing the rest of the body. Current research is exploring the powerful potential of combining radiation, immunotherapy, and nanotechnology in a single treatment approach. Radiation therapy can cause cancer cells to die and release tumour antigens, which can be recognized by the immune system. When this process is paired with nanovaccines or antibody-stimulating nanoparticles, the anti-tumour immune response can be significantly amplified. This multimodal therapy has the potential to not only destroy the tumour but also activate a lasting immune defense, which could improve overall survival for patients with brain malignancies.

ADVANCES AND APPLICATIONS

Neuro-oncology is a rapidly advancing field that focuses on treating brain and spinal cord tumours. A major challenge is delivering therapeutic drugs to tumours while protecting healthy tissue. Nanotechnology offers a solution by enabling targeted therapy that improves treatment effectiveness while reducing adverse effects. Nanoparticles (NPs) can be engineered to specifically target tumour cells. For example, they can be designed with surface ligands that attach to receptors overexpressed on tumour cells. Nanocarriers like liposomes, polymeric nanoparticles, and dendrimers can encapsulate chemotherapy drugs, allowing for controlled, sustained release. This localized delivery minimizes damage to surrounding brain tissue and reduces systemic side effects on vital organs like the liver and kidneys. Some NPs, such as lipid-based solid lipid nanoparticles (SLNs), can even cross the blood-brain barrier (BBB), a significant obstacle in neuro-oncology [43]. The use of nanotechnology also enhances drug efficacy. By improving the stability and solubility of anti-cancer drugs, nanoparticles ensure they remain active longer in the body. The Enhanced Permeability and Retention (EPR) effect allows NPs to accumulate and remain in tumour tissue for extended periods, boosting the drug concentration at the site of the cancer [44]. Furthermore, functionalized NPs can co-deliver multiple therapeutic agents, such as chemotherapy and immunotherapy drugs, to combat drug resistance and improve treatment outcomes. This precision-based approach is also revolutionizing diagnosis. Theranostics are multi-functional nanoparticles used for both therapy and diagnosis. They allow for real-time monitoring of a tumour's response to treatment, enabling clinicians to adjust therapies for individual patients and ultimately improve their prognosis [45].

LIMITATIONS AND CHALLENGES

While nanotechnology holds great promise for medical applications, particularly in neuro-oncology, significant challenges remain before it can be widely used in clinical settings. The main hurdles are potential neurotoxicity, difficulties in large-scale manufacturing, and a lack of clear regulatory guidelines. Nanoparticles (NPs) can cross the blood-brain barrier, which is both a benefit and a risk. Once inside the brain, certain NPs, especially those made of metal and carbon, can cause oxidative damage and inflammation in neural cells [46]. Long-term exposure may lead to mitochondrial damage and impaired neuronal signaling. Another concern is that NPs could interfere with neurotransmitter release and synaptic transmission. More research is needed to ensure the long-term safety of these materials. Bringing nanotechnology from the lab to large-scale production is a major obstacle. It's difficult to consistently produce NPs with uniform size, composition, and surface properties, all of which are crucial for consistent therapeutic effects [47]. The complex methods used to create them are hard to standardize across different batches. Additionally, high production costs and challenges in maintaining sterility and stability during long-term storage further complicate the process. The regulatory framework for nanomedicine is still in its early stages. Unlike traditional drugs, NPs interact with biological systems in complex ways, and there are no standardized protocols for evaluating their toxicity, how they are distributed in the body, or their long-term effects. This makes it difficult for regulatory bodies like the FDA and EMA to create consistent guidelines.

Another major concern is the risk of off-target effects and unexpected immune responses, which could lead to inflammation and systemic toxicity[48]. It will take collaborative effort from researchers, industry, and regulators to establish the necessary safety guidelines for clinical approval.

FUTURE DIRECTIONS OF NANOTECHNOLOGY IN NEURO-ONCOLOGY

Nanotechnology is being explored to improve neuro-oncology treatments by overcoming challenges and leveraging new opportunities. Artificial intelligence (AI) and machine learning (ML) are enhancing the development and clinical application of nanomaterials for brain tumours. Innovations are focusing on improving drug delivery, tumour targeting, and diagnostics [49]. One promising area is stimuli-responsive nanoparticles that release drugs in response to specific cues in the tumour environment, like pH or temperature. Combining nanotechnology with immunotherapy is another key development. Nanoparticles can deliver immune checkpoint inhibitors or tumour antigens to stimulate an immune response against brain tumours [50]. Researchers are also using nanovaccines to prepare the immune system for better tumour detection and destruction. Nanotechnology is also improving diagnostic imaging. Quantum dots and gold nanoparticles are being used to enhance contrast in MRI and other scans, allowing for earlier tumour detection and better monitoring of treatment response. AI and ML are instrumental in advancing nanotechnology for neuro-oncology. They can analyze vast datasets to predict optimal nanoparticle designs, enhance drug delivery systems, and create personalized treatment plans. ML algorithms can predict patient responses to nanomedicine, helping clinicians choose the best nanoparticle formulations for individual patients [51]. AI-driven systems are also speeding up the synthesis and characterization of new nanomaterials, reducing the time and cost of research. Furthermore, AI-powered imaging can track nanoparticles in real time, offering a deeper understanding of how they interact with brain tumours [52]. Continuous innovation in nanomaterial design is improving the efficacy and safety of these therapies. A significant breakthrough is the development of theranostic nanoparticles that can both diagnose and treat tumours, enabling personalized and adaptive therapies. Researchers are also creating biodegradable nanomaterials to reduce long-term toxicity and ensure they can be safely excreted from the body. Surface modifications, such as adding ligands or antibodies, are being used to help nanoparticles more effectively cross the blood-brain barrier and target tumours [53]. The development of nanorobots and self-assembling nanostructures shows future potential for highly specific, minimally invasive brain tumour treatments [54].

CONCLUSION

In conclusion, the formidable challenges in treating central nervous system tumours, driven by obstacles like the blood-brain barrier, tumour heterogeneity, and resistance to conventional therapies, necessitate innovative approaches. Nanotechnology has emerged as a profoundly promising field, offering solutions that fundamentally change how we diagnose and treat these conditions. The core strength of nanomedicine lies in its ability to surmount biological barriers, enabling the precise and targeted delivery of therapeutic agents. By encapsulating drugs, genes, and radiosensitizers within nanoparticles, researchers can improve drug efficacy, reduce systemic toxicity, and directly address the tumour microenvironment. Furthermore, the development of theranostic nanoparticles is revolutionizing diagnostics, providing a platform for real-time monitoring and personalized treatment adjustments. While the transition from preclinical research to widespread clinical application faces significant hurdles, including potential neurotoxicity, manufacturing scalability, and regulatory complexities, the momentum of the field is undeniable. The integration of nanotechnology with artificial intelligence and personalized medicine is set to accelerate the development of highly effective, safer, and tailored therapies. Ultimately, the fusion of these technologies offers a clear path toward a new era in neuro-oncology, promising improved patient outcomes and a significantly better quality of life for those afflicted with CNS tumours.

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